How Interconnects Work: Traces Between Parallel Planes

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Traces on PCBs are often routed between parallel planes – what can be simpler than that? Well, it is a three-conductor structure that supports propagation of transverse electro-magnetic (TEM) waves as well as waves of the parallel plate waveguide (PPW) –superposition of radial or plane waves. It complicates the things. TEM waves are used to transmit the signal between components. PPW waves are used to deliver power to the components. TEM and PPW waves are both useful but have to be separated. For instance if we launch TEM wave into a trace with ideal equipotentiality of the parallel planes, we can observe the wave propagating strictly along the traces as illustrated here (click to see the animation):

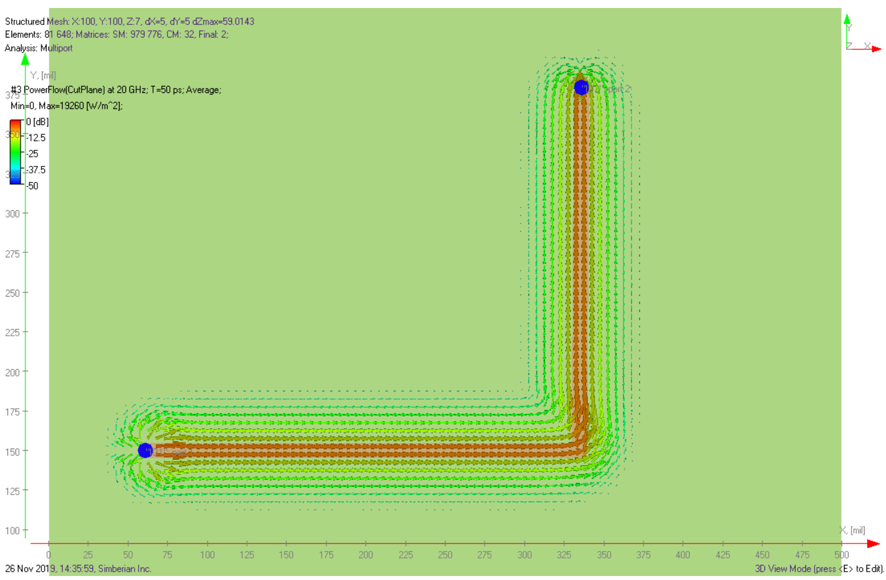

Fig. 1. Power flow density in trace with equipotential planes. Trace segment is excited with with 1 V 50 Ohm, 20 GHz harmonic sourse at the bottom left port. Another port is terminated with 50 Ohm. Both ports are via-ports with signal terminal at the trace and reference terminals simultaneously at the top and bottom planes.

What happens if one of the planes is power plane and another is a ground plane – the equipotentiality cannot be enforced in this case. Here is illustration of what happens with the signal in this case (click on picture to see the animation):

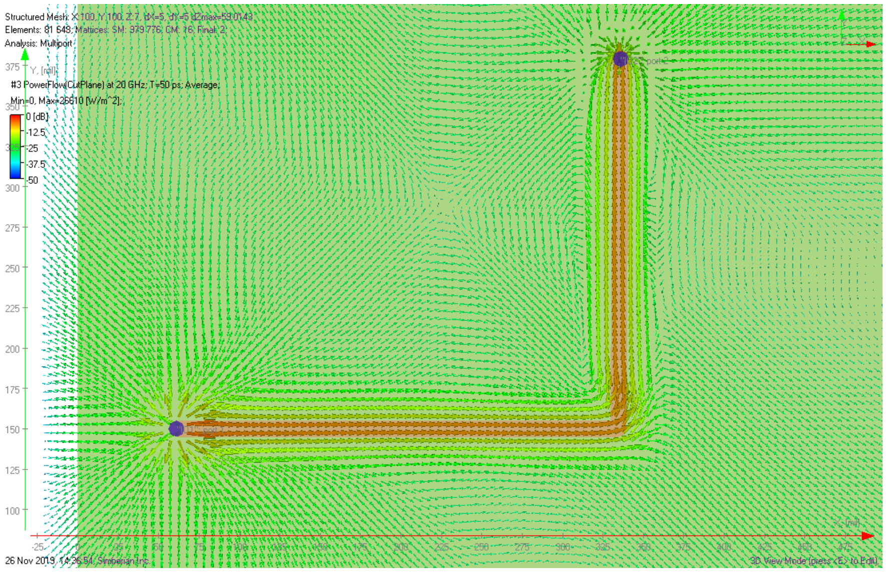

Fig. 2. Power flow density in trace referenced to one plane. Trace segment is excited with with 1 V 50 Ohm, 20 GHz harmonic sourse at the bottom left port. Another port is terminated with 50 Ohm. Both ports are via-ports with signal terminal at the trace and reference terminals at the bottom plane only.

Excitation with the referencing to just one of the planes (GND) causes signal transformation into useful TEM wave as well as into radial waves of PPW. Waves in PPW are unwanted noise – it can cause electromagnetic compatibility or interference (EMC/EMI) problems and unwanted propagation of signal between the components through parallel planes (multi-path propagation). Those effects are practically unpredictable for complex designs. Also, the signal transformation changes the observable trace impedance too. In this simple case, the impedance of the trace referencing just one plane will be about 1 Ohm off on time domain reflectometry (TDR) plot as shown in Fig. 3.

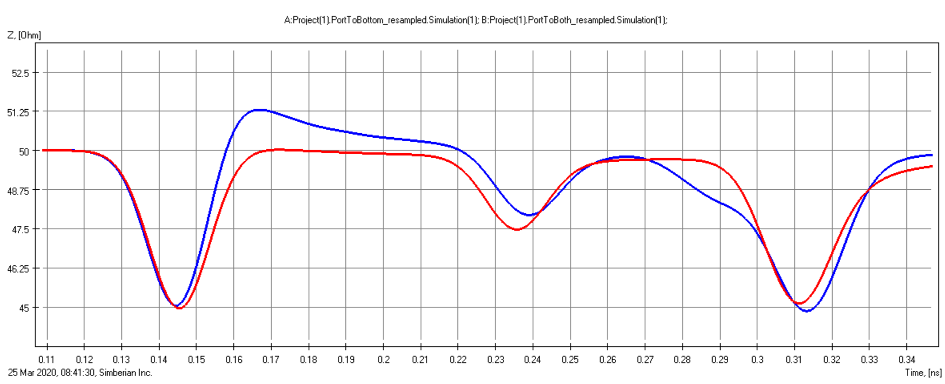

Fig. 3. TDR of trace with two equal-potential reference planes (red plot) and TDR of trace with reference to just one plane at the excitation location (blue plot).

The first case from Fig. 1 with ideally equipotential planes is just a model – 2 ports from the trace to the planes are used to excite only TEM wave. Port construction is illustrated on top picture in Fig. 4.

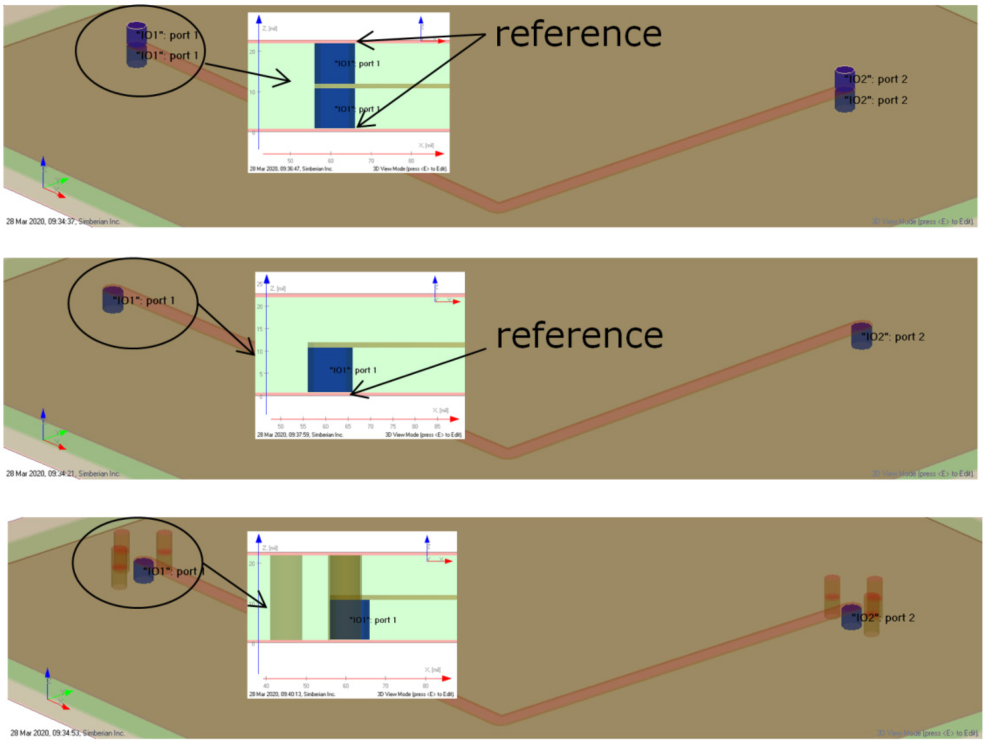

Fig. 4. Trace with ports to two planes (top picture), with ports to bottom plane (middle picture) and port to bottom plane and short-circuiting vias around each port.

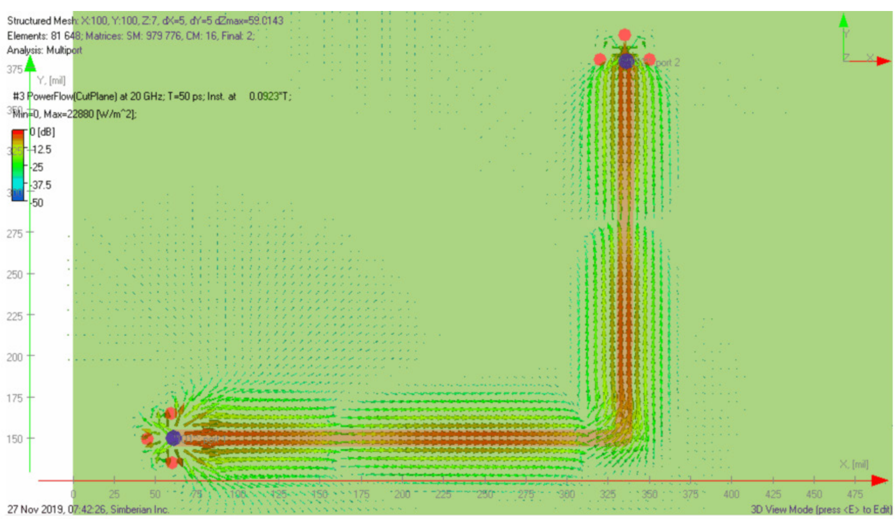

Fig. 5. Power flow density in trace with enforced equipotentiality. Trace segment is excited with with 1 V 50 Ohm, 20 GHz harmonic sourse at the bottom left port. Another port is terminated with 50 Ohm. Both ports are via-ports with signal terminal at the trace and reference terminals at the bottom plane only. Planes are connected with 3 vias around each port, to enforce the equipotentiality.

Such port construction removes interaction between TEM and PPW completely – the excitation port up has -1 V source and port down is +1 V. That produces no voltage between the planes exactly. On the other hand, port from the trace to just bottom plane with +1 V excitation as shown in the middle picture of Fig. 4 produces waves in both transmission line and transmission plane. How to avoid or reduce such transformations in real life? With short-circuiting or stitching vias connecting the reference planes and enforcing the equipotentiality as shown at the bottom picture on Fig. 4. The vias make planes equipotential locally and signal goes mostly into the TEM mode of the trace as illustrated in Fig. 5. The most critical location for such enforcement is the location of signal via. If a few stitching vias are placed electrically close (within quarter of wavelength in dielectric at Nyquist frequency) to each signal via, the PPW waves will be substantially reduced and the signal will be transformed into the TEM wave again as illustrated on Fig. 5. Such equipotentiality enforcement is not possible if two reference planes of the trace cannot be connected or stitched. **Stackup must be re-designed to allow the plane to plane stitching around the launch vias and, possibly, along the traces.** Otherwise the localization of the transition is compromised with unpredictable consequences [1], [2].

Power flow density is used to illustrate the concept of signal transformation. Planes are assumed infinite that is simulated with Perfectly Matched Layer (PML) boundary conditions.

1. Y. Shlepnev, Life beyond 10 Gbps: Localize or Fail!, Signal Integrity Journal, April 18, 2018.
2. "How Interconnects Work" demo-videos on launch and via localization at https://www.simberian.com/ScreenCasts.php or at Simbeor channel on YouTube https://www.youtube.com/user/simbeor/videos